**Inclusive Production of Strange Particles
in $p\bar{p}$ Collisions at $\sqrt{s} = 630 \text{ GeV}$ with UA1**

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Abstract

We have analysed a sample of 2.36 million minimum bias events produced in $p\bar{p}$ collisions at $\sqrt{s} = 630 \text{ GeV}$ in the UA1 experiment at the CERN $S\bar{p}\bar{p}S$ collider. We have studied production of K_s^0 s, Λ s and $\bar{\Lambda}$ s particles with transverse momenta (p_T) up to $7 \text{ GeV}/c$ and $K^\pm$ up to $2 \text{ GeV}/c$. The kaon data are compared with a recent QCD prediction and are found to be in good agreement. The $\langle p_T \rangle$ for K_s^0 s, Λ s and $\bar{\Lambda}$ s is seen to increase as a function of the charged particle multiplicity and is compared with charged particle production.

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1. Introduction

Results are given from analysis of a single collider run at $\sqrt{s} = 630 \text{ GeV}$, in 1987, when a high statistics sample of 2.36 million minimum bias events was recorded with the UA1 detector^[1]. All the data discussed in this paper were recorded with a trigger requiring one or more particles in either forward arm. The trigger acceptance was $(96 \pm 2)\%$ of the full non-single diffractive inelastic cross-section. Background events from beam-gas were eliminated by the requirement of a good collision vertex. The average luminosity during the run was only about $10^{27} \text{ cm}^{-2} \text{ s}^{-1}$ and the contribution from double interactions in the same trigger interval is therefore negligible.

Strange particles are identified by the reconstruction of secondary decay vertices well separated from the primary production vertex. K_s^0 s, Λ s and $\bar{\Lambda}$ s are reconstructed as V^0 vertices and $K^\pm$ from its 3-prong decay mode : $K^\pm \rightarrow \pi^+ \pi^- \pi^\pm$. The invariant mass of the secondaries was then used for particle identification [2]. Signal and background of the mass distribution were parametrized and fitted in order to determine the number of K_s^0 s, Λ s and $\bar{\Lambda}$ s for a number of p_T bins up to $7 \text{ GeV}/c$. The p_T distribution is compared with QCD and the $\langle p_T \rangle$ dependence and the particle multiplicity is investigated. The long decay time and small branching fraction ($\sim 6\%$) of $K^\pm \rightarrow \pi^+ \pi^- \pi^\pm$ decay mode limits the statistics of the p_T distribution of $K^\pm$ which is measured only up to $2 \text{ GeV}/c$.

2. Inclusive Neutral Strange Hadrons

In order to minimize biases with this high statistics data sample, a recalibration of the Central Detector (geometrical and drift parameters) was carried out with a new technique using data with two opposite magnetic field settings ($\pm 0.7 \text{ T}$). In parallel the measurement of the coordinate along the wires by current division was recalibrated using the data. Acceptance tables were generated by a single track Monte Carlo. Charged hadrons were reconstructed with a reasonable acceptance in the pseudorapidity interval $-3 < \eta < +3$, down to a lower momentum cut-off of $0.2 \text{ GeV}/c$. Since in the very forward region the charged multiplicity is high which in turn results in large combinatorial background for V^0 reconstruction, we limit the pseudorapidity ranges for K_s^0 reconstruction to $|\eta| < 2.5$ and for Λ and $\bar{\Lambda}$ reconstruction to $|\eta| < 2.0$.

Well measured tracks with $\delta p/p < 30\%$ not associated to the primary vertex were used as track candidates for V^0 reconstruction. Positive and negative track pairs fitting to a secondary vertex with a reasonable χ^2 were retained and an invariant mass test performed using the measured track parameters. Track pairs with a reconstructed mass within 60 MeV of the K_s^0 mass or 40 MeV of the Λ^0 mass were retained. Clear peaks for the K_s^0 and Λ^0 are observed. Fitting the K_s^0 mass spectrum with a Breit-Wigner function and a linear background yields $62000 \pm 250 \text{ } K_s^0$ in the mass range $0.477 < m(\pi^+ \pi^-) < 0.517 \text{ GeV}$ with a purity of 93%. Fits of the Λ and $\bar{\Lambda}$ mass distributions yield 6173 ± 84 and 6183 ± 84 events respectively in the mass range $1.112 < m < 1.122 \text{ GeV}$ with a purity of 88%.

Detailed V^0 reconstruction efficiencies were evaluated as a function of η , azimuthal angle (ϕ) around the beam and p_T using a Monte Carlo program that generated and decayed K_s^0 s, Λ s and $\bar{\Lambda}$ s and superimposed these decays on real data events. Fig. 1a and Fig. 1b show the p_T distribution for K_s^0 and Λ plus $\bar{\Lambda}$ respectively.

In a previous analysis^[3], a functional form inspired by QCD and first introduced by UA1^[4]

Figure 1: a $p\bar{p} \rightarrow K_S^0 + X$ invariant cross-section and fitted function.

has been used to fit the p_T spectrum for charged particles.

$$E \frac{d^3 \sigma}{dp^3} = \frac{A}{(1 + p_T/p_T^0)^n}.$$

As stressed by Hagedorn^[5], p_T^0 and n are highly correlated when fitted over a limited range of p_T . In this experiment, with an analysis^[3] of the charged particle p_T spectrum it was possible to fit the function from $p_T > 0.18 \text{ GeV}/c$ up to p_T of $25 \text{ GeV}/c$ with $n = 8.91 \pm 0.13$, $p_T^0 = 1.32 \pm 0.05 \text{ GeV}/c$. For fitting the $K_S^0 p_T$ spectrum, we have chosen to fix $n = 8.9$ and vary p_T^0 . Our best fit in the range $|\eta| < 2.5$ gave $p_T^0 = 1.565 \pm 0.019 \text{ GeV}/c$, $A = 16.38 \pm 0.81 \text{ mb GeV}^{-2}$ and this is displayed in Fig. 1a.

The Λ and $\bar{\Lambda}$ p_T distribution is harder than that for $K_S^0 p_T$ spectrum and is fitted with a simple exponential function:

$$E \frac{d^3 \sigma}{dp^3} = a e^{-b p_t}.$$

In this case in the range $|\eta| < 2.0$ the best fit gave $a = 1.90 \pm 0.11 \text{ mb GeV}^{-2}$ and $b = 2.21 \pm 0.03 (\text{GeV}^{-1})$ and this is shown in Fig. 1b.

In order to check the systematic effect of the choice of the fitting function, we also fitted the Λ and $\bar{\Lambda}$ p_t distribution with the power law. We found that the derived results such as

Figure 1: $b\ p\ \bar{p} \rightarrow \Lambda\ \text{or}\ \bar{\Lambda} + X$ invariant cross-section and fitted exponential.

average p_t , yield, etc. are consistent with each other. The small differences are taken as the systematic errors [2].

3. Comparison with QCD

A comparison of K_S^0 invariant cross-sections as a function of p_T for UA1 (630 GeV) and CDF (630 and 1800 GeV) data [7] is shown in Fig. 2.

The UA1 630 GeV data and CDF 1800 GeV data cover a similar p_T range up to 7 GeV/c . The CDF 630 GeV data agree well with the UA1 data but are limited in statistics and are measured only up to 3 GeV/c . Included on this plot are also the data we have obtained by reconstruction of the $K^\pm$ by its $\pi^+\pi^-\pi^\pm$ decay mode. After background subtraction we obtained $1450 \pm 59\ K^+$ and $1710 \pm 64\ K^-$. The larger number of reconstructed K^- relative to K^+ is due to the special arrangement of the wires of the UA1 central detector and the magnetic field which result in higher acceptance for negative tracks and thus more $\pi^-\pi^-\pi^+$ combinations than $\pi^+\pi^+\pi^-$. The limited statistics of this sample limits the p_T measurement up to 2 GeV/c . We have also plotted the new next to leading order (NLO) QCD calculation by Borzumati et al [6]. The three curves correspond to different choices of the renormalization scale, namely $p_T/2$, p_T and $2p_T$. There is a good agreement with the QCD calculation which itself only goes down to 1 GeV/c though there is some indication that the data are slightly lower at lower values of p_T .

Figure 2: Comparison of K_S^0 invariant cross-sections as a function of p_t for UA1 (630 GeV) and CDF (630 and 1800 GeV) [7] data. The invariant cross-section of $K^\pm$ from UA1 (630 GeV) is also shown.

4. Dependence of Mean p_T on Charged Particle Multiplicity

We have measured the $\langle p_T \rangle$ for K_S^0 s, $(\Lambda + \bar{\Lambda})$ and charged particles as a function of the charged track multiplicity $N_\pm$. The K_S^0 and charged particle data, in the range $|\eta| < 2.5$, were divided into 5 bins of $N_\pm$ namely $N_\pm < 20$, $20 \leq N_\pm < 30$, $30 \leq N_\pm < 40$, $40 \leq N_\pm < 50$ and $N_\pm \geq 50$. The $(\Lambda + \bar{\Lambda})$ data, in the range $|\eta| < 2.0$, were divided into 3 bins of $N_\pm$ namely $N_\pm < 20$, $20 < N_\pm < 40$ and $N_\pm > 40$. Within each bin the p_T distributions were fitted with the functional forms given in section 2 and the $\langle p_T \rangle$ computed analytically by integrating from $p_T = 0$. For the fits to the K_S^0 and charged particle data the power n was fixed to 8.9 as in section 2. Fig. 3 shows the average p_t as a function of the charged track multiplicity for charged hadrons, K_S^0 , and $(\Lambda + \bar{\Lambda})$. In all cases $\langle p_T \rangle$ is seen to increase with charged particle multiplicity. For the same particle multiplicity it can be seen that $\langle p_T \rangle$ for K_S^0 is approximately 20% higher than that for charged hadrons, except at the lowest multiplicities, and that the $\langle p_T \rangle$ for $(\Lambda + \bar{\Lambda})$ is almost a factor of 2 greater than that for K_S^0 . Table 1 and table 2 show the $\langle p_T \rangle$ values obtained. A more detailed discussion of the charged particle data is given in reference 3.

Figure 3: Average p_t as a function of charged track multiplicity per unit pseudorapidity for charged hadrons, K_S^0 , and $\Lambda + \bar{\Lambda}$.

	$\langle p_t(\text{Charged Hadrons}) \rangle [GeV/c]$	$\langle p_t(K_S^0) \rangle [GeV/c]$
$N_{ch} < 20$	0.394 ± 0.001	0.335 ± 0.010
$20 \leq N_{ch} < 30$	0.411 ± 0.001	0.432 ± 0.013
$30 \leq N_{ch} < 40$	0.437 ± 0.001	0.498 ± 0.009
$40 \leq N_{ch} < 50$	0.457 ± 0.001	0.552 ± 0.010
$N_{ch} \geq 50$	0.485 ± 0.001	0.620 ± 0.010

Table 1: The average p_t as a function of charged track multiplicity for charged hadrons and K_S^0 .

	$\langle p_t(\Lambda + \bar{\Lambda}) \rangle (GeV/c)$
$N_{ch} < 20$	0.63 ± 0.02
$20 \leq N_{ch} < 40$	0.82 ± 0.02
$N_{ch} \geq 40$	0.98 ± 0.01

Table 2: The average p_t as a function of charged track multiplicity for $\Lambda + \bar{\Lambda}$.

5. K_S^0 Production Relative to Charged Hadrons

Fig. 4 shows the quantity $\langle K_S^0 \rangle / \langle h^- \rangle$ vs $\langle N_- \rangle$ of our measurement together with $\langle K_S^0 \rangle$ vs $\langle N_- \rangle$ from heavy ion experiments at CERN^{[8][9]}. The quantity $h^\pm$ is the acceptance corrected charged track multiplicity. $N_\pm$ and N_- are the observed charged track multiplicity and the negative charged track multiplicity respectively. $\langle K^\pm \rangle / \langle h^\pm \rangle$ as a function of $N_\pm$ from our measurement and that from E735^[10] are also shown in the plot. For the E735 data, we used their K/π measurements and then divided them by the π/h measurement from the UA2 experiment^[11], as in our case. Table 3 lists the numerical values corresponding to Fig. 4

Figure 4: Relative production of K_S^0 with respect to half number of all the observed charged hadrons ($p\bar{p}$ collider^[10]) or to all the negative hadrons (heavy ion experiments [8, 9]).

We found that the results from the colliders agree within errors, while they are different from the results from the heavy ion experiments. This difference could be partly explained in the following way.

particle	$N_{\pm}/2$	$\langle 2K_S^0 \rangle / \langle h^{\pm} \rangle$
K_S^0	14	0.077 ± 0.005
	26	0.079 ± 0.004
	36	0.080 ± 0.005
	46	0.079 ± 0.004
	66	0.075 ± 0.004
	$N_{\pm}/2$	$\langle K^{\pm} \rangle / \langle h^{\pm} \rangle$
$K^{\pm}$	13	0.085 ± 0.010
	24	0.086 ± 0.009
	34	0.085 ± 0.011
	57	0.080 ± 0.008

Table 3: Relative production of K_S^0 or $K^{\pm}$ with respect to the charged hadrons as a function of charged track multiplicity.

We know from the quark model that $K_S^0 = \frac{1}{\sqrt{2}}(d\bar{s} + \bar{d}s)$. In $p\bar{p}$ collisions we have both valence d quarks and valence $\bar{d}$ quarks. They can combine with the sea quark s and antiquark $\bar{s}$. So both $d\bar{s}$ and $\bar{d}s$ components will contribute to the K_S^0 formation. In heavy ion experiments there are only valence quarks in the beam and target, but no valence antiquarks. So only the $d\bar{s}$ ($\bar{s}$ is from the sea) component will contribute to the K_S^0 formation. Therefore we expect the K_S^0 yield density with respect to the negative hadrons in $p\bar{p}$ collisions to be approximately twice as high as that in heavy ion collisions. This is clearly reflected in the data plotted in Fig. 4.

6. $\Lambda + \bar{\Lambda}$ Production Relative to Charged Hadrons

Fig. 5 shows our measurement of the ratio $\langle \Lambda \rangle / \langle h^- \rangle$ vs $\langle N_- \rangle$ together with that from E735^[12] at Tevatron and $\langle \Lambda \rangle$ vs $\langle h^- \rangle$ from NA35^[9] and NA36^[8].

Table 4 lists the numerical values for the plots.

$N_{\pm}/2$	$\langle \Lambda + \bar{\Lambda} \rangle / \langle h^{\pm} \rangle$
12	0.0105 ± 0.0014
24	0.0136 ± 0.0013
34	0.0187 ± 0.0013
44	0.0220 ± 0.0019
64	0.0241 ± 0.0014

Table 4: Relative production of Λ and $\bar{\Lambda}$ with respect to the charged hadrons as a function of charged track multiplicity.

Figure 5: Relative production of $\Lambda + \bar{\Lambda}$ with respect to all the observed charged hadrons ($p\bar{p}$ collider[12]) or Λ with respect to all the negative hadrons (heavy ion experiments [8, 9]).

We can see from Fig. 5 that the results from the colliders and heavy ion experiments agree with each other very well. This is quite different from the K_S^0 production case. This is consistent with the idea that the Λ baryon is composed of uds valence quarks. No valence antiquarks are needed to form Λ s. Therefore in $p\bar{p}$ collisions the valence antiquarks in the $\bar{p}$ beam do not contribute to the Λ production, at least not directly. In the heavy ion collisions there are only valence quarks in the beam and in the target which are the only ingredients for Λ production. Hence, $p\bar{p}$ and heavy ion collisions should behave similarly in this study, at least as far as there is no Quark Gluon Plasma (QGP) effect in the heavy ion collision data used for comparison. The agreement between the two different collider energies also implies that the ratio is not sensitive to moderate variations in the center of mass energy which is indeed one characteristic of the minimum bias events in the $p\bar{p}$ collider case because the dependence is expected to be logarithmic.

7. Summary

The $K_S^0, \Lambda + \bar{\Lambda}$ p_t production cross-sections were measured with high precision. The results are in good agreement with other $p\bar{p}$ collider experiments. The K_S^0 and $K^\pm$ production cross-sections are also in agreement with a recent NLO QCD calculation.

The relative productions of $K_S^0, \Lambda + \bar{\Lambda}$ compared to charged hadrons as a function of charged track multiplicity are in agreement with other $p\bar{p}$ collider experiments and heavy ion experi-

ments suggesting that there is no strong quark-gluon plasma effect in the heavy ion collision experiments used for comparison.

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References

- [1] A. Astbury et al., Nucl. Instr. Meth. A238 (1985) 288.
C. Albajar et al., Nucl. Phys. B335 (1990) 261.
- [2] "Inclusive Production of Strange Particles at the CERN Proton-Antiproton Collider",
C. H. Tan, Ph.D. thesis, 1994, MIT, (unpublished).
- [3] "Transverse Momentum Spectra of Charged Particles in $p\bar{p}$ Collisions at $\sqrt{s} = 630$
 GeV ",
G. Bocquet et al., accepted by Phys. Lett. B.
- [4] G. Arnison et al., Phys. Lett. 118B (1982) 167.
M. Brenner et al., Z. Phys. C27 (1985) 329.
F. Abe et al., Phys. Rev. Lett. 61 (1988) 1819.
- [5] R. Hagedorn, Riv. Nuovo Cim. 6,10,1 (1984).
- [6] F.M. Borzumati, G. Kramer, Z. Phys. C67, 137-142 (1995).
- [7] F.Abe et al., Phys. Rev. D40 (1989) 3791.
- [8] E.Andersen et al., Nucl. Phys. A553 (1993) 817.
E.Andersen et al., Phys.Lett. 316B (1993) 603.
- [9] S.Nagamiya et al., Nucl. Phys. A544 (1992) 5.
J.Bartke et al., Z.Phys. C48 (1990) 191.
- [10] T.Alexopoulos et al., Phys. Rev. D48 (1993) 984.
T.Alexopoulos et al., Phys. Rev. Lett. 64 (1990) 991.
- [11] D.Ward, CERN-EP/87-178 (1987).
M.Banner et al., Phys.Lett. 122B (1983) 322.
M.Banner et al., Z.Phys. C27 (1985) 329.
- [12] T.Alexopoulos et al., Phys.Rev. D46 (1992) 2773.